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A series of ten composite solid propellants with systematically varied formulation parameters has been characterized with respect to the dependence of burning rate on pressure and product crossflow velocity over a wide range of these variables. Predictions of the erosive burning characteristics of these formulations made with a simple model based on columnar diffusion flame bending were found to agree fairly well with data except at low pressure con-

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ditions where propellant heterogeneity is relatively unimportant. A second-generation, considerably more fundamental model of composite propellant combustion (with and without crossflow) which includes both the flame bending mechanism and a turbulent transport property augmentation erosive burning mechanism also yielded predictions in good agreement with data, even in the low pressure region where the first generation model failed, for five of the six formulations against which it has been tested to date. The most important factor affecting the sensitivity of composite propellant burning rate to crossflow was found to be the base (no crossflow) burning rate versus pressure characteristics of the propellant, low burning-rate propellants being more sensitive to cross flow. As an important example, three formulations with widely different compositional and particle size parameters but essentially equal base burning rate behavior exhibited nearly identical erosive burning characteristics.

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(6) AN INVESTIGATION OF THE EFFECTS OF FORMULATION PARAMETERS ON EROSIVE BURNING OF COMPOSITE PROPELLANTS*

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ABSTRACT

A series of ten composite solid propellants with systematically varied formulation parameters has been characterized with respect to the dependence of burning rate on pressure and product crossflow velocity over a wide range of these variables. Predictions of the erosive burning characteristics of these formulations made with a simple model based on columnar diffusion flame bending were found to agree fairly well with data except at low pressure conditions where propellant heterogeneity is relatively unimportant. A second-generation, considerably more fundamental model of composite propellant combustion (with and without crossflow) which includes both the flame bending mechanism and a turbulent transport property augmentation erosive burning mechanism also yielded predictions in good agreement with data, even in the low pressure region where the first generation model failed, for five of the six formulations against which it has been tested to date. The most important factor affecting the sensitivity of composite propellant burning rate to crossflow was found to be the base (no crossflow) burning rate versus pressure characteristics of the propellant, low burning-rate propellants being more sensitive to cross flow. As an important example, three formulations with widely different compositional and particle size parameters but essentially equal base burning rate behavior exhibited nearly identical erosive burning characteristics.

INTRODUCTION AND BACKGROUND

The development of nozzleless rocket motors and the increasing use of low port-to-throat area ratio solid propellant grain configurations for attainment of higher propellant loading fractions in nozzled motors are leading to an increase in the frequency and severity of alteration of solid propellant motor interior ballistics from those to be expected on the basis of no-crossflow burning rate data. This alteration in burning rate caused by high velocity crossflow through the grain port is generally referred to as erosive burning. For design optimization, it is necessary that the motor designer be able to predict these ballistic alterations accurately in order to properly compensate for them. In addition, if the formulation characteristics influencing the sensitivity of propellant burning rate to transverse flows are identified, the propellant chemist may be able to optimize this dependency within his other constraints. The use of

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the word "optimize" as opposed to "minimize" should be noted here. In a nozzleless motor, the decrease in pressure from the head end to the aft end of the grain tends to result in slower burning at the aft end in the absence of erosive effects. Depending upon the sensitivity of the formulation to crossflow, the increasing crossflow velocity down the grain port may lead to under-compensation, exact cancellation, or over-compensation of the pressure effect. To minimize sliver effects (uneven burnout with a resultant long pressure tailoff) the formulator would generally like to be able to tailor his propellant so that the pressure and crossflow velocity effects on burning rate just cancel each other out. This is discussed in more detail in Reference 1.

In the current Atlantic Research program on which this paper is based, the erosive burning of composite solid propellants is being experimentally and analytically studied. The program includes: (1) development of a simplified (Generation 1) model for prediction of erosive burning of a composite propellant, given the non-erosive burning rate-pressure relationship for that formulation; (2) development of a more fundamental (Generation 2) composite propellant combustion model for prediction of burning rate as a function of pressure and crossflow velocity (including prediction of the no-crossflow burning rate-pressure relationship) given only the propellant composition and particle size distributions for the various solid ingredients; and, (3) experimental measurement of the erosive burning characteristics (at crossflow velocities up to Mach 1) of a series of propellants with systematically varied compositions and ingredient particle sizes. The simplified first generation model has been described in detail in References 2 and 3 while the more sophsiticated second generation model has been presented in References 4 and 5. In this paper, erosive burning data obtained on this program to date will be presented and compared with predictions made with the first and second generation models, and the effects of various formulation parameters on the sensitivity of composite propellant burning rate to crossflow will be delineated.

The first generation erosive burning model is a very simplified one which does not include any detailed analysis of the combustion mechanisms associated with composite propellant burning. This model does not include a capability for prediction of burning rate versus pressure in the absence of crossflow but instead employs no-crossflow burning rate data (available from relatively inexpensive strand burning tests) as input. As explained in detail in References 2, 3, and 6, the mechanism by which crossflow is hypothesized in this model to affect the burning rate of composite propellants involves the shortening of the distance (measured normal to the surface) associated with the mixing of the columns of fuel and oxidizer gas leaving the surface. This shortening of the mixing distance is postulated to result from "pushing over" or "bending" of the oxidizer and fuel gas columns by the crossflow. Details of the geometrical picture associated with the postulated mechanism are presented in Reference 6. It must be emphasized that this model is meant to apply only to composite propellants in which there is significant heat release associated with reaction between fuel and oxidizer decomposition products. Other mechanisms must be invoked to explain the erosive burning of homogeneous propellants (or HMX-oxidized composites, which do not have a significant O/F flame).

With the second generation model, burning rate is predicted as a function of pressure and crossflow velocity (including the limiting case of zero crossflow) given only propellant composition and ingredient size data. As discussed in Reference 5, this model initially included only the flame-bending mechanism for treatment of the effects of crossflow velocity on burning rate; however, in this form the model was found to, in general, badly underpredict erosive burning. Accordingly, a second erosive burning mechanism involving crossflow-induced turbulence augmentation of transport properties (heat and mass transport) was subsequently built into the model.

Major advantages of the first generation model are its relative simplicity (reflected in low computational requirements) and its ability to take advantage of relatively inexpensive strand data rather than being required to accomplish the difficult a priori prediction of no-crossflow burning rate versus pressure characteristics of each propellant considered. (This latter point is particularly important as regards catalyzed formulations.) The second-generation model, on the other hand, is on much stronger fundamental grounds than the first generation model and, moreover, does not require input burning rate data. These advantages are gained, however, at the cost of considerably more complex and lengthy computational requirements. In addition, there are three empirical constants (associated with global kinetics) imbedded in the second-generation model which, while truly invariant within a given propellant family, must be optimized for each new family. At this point the effect of catalysts on the values of these constants is not well quantified.

EXPERIMENTAL

EQUIPMENT

The experimental test apparatus and procedures employed in this study of erosive burning are described in detail in Reference 2. A schematic of the basic test apparatus is presented as Figure 1. A cylindrically perforated 6C4 driver grain (15.2 cm outside diameter, 10.2 cm inside diameter) whose length is chosen to give the desired operating pressure for a given test, produces a high velocity gas flow through a transition section into a rectangular test section which contains the test grain (generally the same formulation as the driver grain). The contoured transition section is approximately 10 cm (4 inches) long. The test grain extends from the test section back through the transition section to butt against the driver grain in order to eliminate leading edge effects which would be associated with a test grain standing alone. The test grain is approximately 30 cm (12 inches) long (plus the 10 cm extending through the transition section) by 1.90 x 2.50 cm (3/4 inch and 1 inch) web and burns only on the 1.90 cm face. The flow channel of the test section is initially 1.90 cm x 1.90 cm (3/4 inch x 3/4 inch), opening up to 1.90 cm x 4.45 cm (3/4 inch x 1-3/4 inch) as the test propellant burns back through its 2.54 cm (1 inch) web. For high Mach number tests, the apparatus is operated in a nozzleless mode with the gases choking at or near the end of the test grain, while for lower Mach number tests, a 2-dimensional nozzle is installed at the end of the test channel.

During each test, pressure and crossflow velocity varies with time and location along the test grain. (For the nozzleless tests, pressure varies

significantly with time and location, while crossflow velocity varies considerably with location but not significantly with time. For tests using a nozzle with an initial port to throat area ratio of 1.5 or higher, on the other hand, pressure does not vary strongly with location but does rise with time due to the progressivity of the driver grain, while crossflow velocity varies strongly with time and slightly with location.) These variations permit design of tests to yield considerable burning rate-pressure-crossflow velocity data in relatively few tests, provided that these parameters can be measured continuously at several locations along the test grain. These parameters are measured in the following manner.

The burning rate is directly measured by photographing the ablating grain with a high-speed motion picture camera through a series of four quartz windows located along the length of the test section. Frame by frame analysis of the films permits determination of instantaneous burning rate as a function of time at each of the four window locations.

For nozzled cases, the measured location of the burning propellant surface at each window as a function of time, together with the known constant throat area, permits straightforward calculation of the crossflow velocity as a function of time. However, the very sensitive dependence of Mach number on area ratio for $M > 0.5$ makes calculation of crossflow velocity from area ratio measurement quite poor for nozzleless cases. Accordingly, for these tests, stagnation pressure is determined at the aft end of the test section and used in combination with the driver chamber pressure for calculation of the stagnation pressure in the test section as a function of time and position. Static pressure wall taps at each window location are used for measurement of static pressure as a function of time for both nozzled and nozzleless cases. From the static and stagnation pressure values determined as a function of time and position down the test section, crossflow Mach Number and velocity are calculated as a function of time at each window location in the test section for the nozzleless cases.

TEST MATRIX

The purpose of the experimental part of this program is to characterize, over a wide range of pressure and crossflow velocity, the erosive burning behavior of a series of propellants in which various formulation parameters are systematically varied. The total planned propellant test matrix is listed in Table I. At this time, testing of ten of these formulations (1-9,11) is complete. The first five of these formulations contained unimodal oxidizer. It was considered important that initial tests be carried out with such formulations for definition of oxidizer particle size effects under "clean" conditions. In addition, the second generation model was originally developed for unimodal oxidizer formulations (with later extension to multimodal oxidizer cases): accordingly, these initial tests were important for testing and modification of the basic unit model. Formulation 1 (4525) was selected as a baseline HTPB/AP composite propellant. Formulations 2, 3, and 4 (5051, 4685, 4869) represent simple variations from the first formulation aimed at permitting isolation of the effects of oxidizer particle size and base burning rate on crossflow sensitivity, as discussed further below.

In terms of independent variables, Formulation 5 (5542) differs from the baseline formulation only in oxidizer/fuel ratio. Due to this

difference, of course, the flame temperatures differ and, because AP size is held constant, the base burning rate characteristics differ (Formulation 5 having a higher base burning rate). Thus, comparison of the results for these formulations permits definition of the effect of oxidizer/ fuel ratio change at constant oxidizer particle size. With Formulation 7 (5565) on the other hand, oxidizer/fuel ratio is varied from that of Formulation 1, but oxidizer particle sizes are adjusted to give approximately the same zero-crossflow burning rate characteristics for the two formulations, permitting examination of the effect of varying oxidizer/fuel ratio at constant base burning rate. Formulation 8 (5555) is identical to Formulation 7, except for use of much finer oxidizer sizes to yield higher base burning rate, permitting further study of the effect of this parameter on erosion sensitivity. Formulation 11 (6626) is the first metalized propellant studied. This composition was chosen to give approximately the same flame temperature as Formulation 7, while the oxidizer size was adjusted to give approximately the same base burning rate versus pressure curve as obtained with Formulations 1 and 7, allowing determination of any direct affect of aluminum on erosive burning sensitivity.

As may be seen, all of the formulations described above employ a hydroxyl-terminated polybutadiene binder system. Formulations 6 and 9 (7523 and 7605) on the other hand, are polyester based formulations, included for study of the effects of binder system on erosive burning sensitivity. Oxidizer particle sizes in Formulation 6 were chosen to yield no-crossflow burning rate behavior nearly identical to that of Formulation 4, permitting examination of the effect of binder type at fixed base burning rate. A similar comparison may be made between Formulations 5 and 9. (As will be discussed later, base burning rate was found in testing with the HTPB propellant family to be a dominant factor in determining erosive burning sensitivity.)

EXPERIMENTAL RESULTS AND COMPARISON TO THEORY

A rather complete set of data, covering a pressure range of 1 to 5 MPa (10 to 50 atmospheres) and a crossflow velocity range of 180 to 670 m/sec (600 to 2200 ft/sec) has been obtained for Formulation 4525, the baseline formulation. Experimental results are compared with first generation model predictions in Figures 2 and 3 and with second generation model predictions in Figure 4. As may be seen, agreement between first generation model predictions and data is reasonably good. The predicted curves for burning rate versus presure at various crossflow velocities (Figure 2) do seem to group more tightly than the data. That is, as shown more clearly in Figure 3, the model tends to slightly overpredict the burning rate at low crossflow velocities and slightly underpredict at high velocities. As with the other propellants studied, theory and data both indicate increasing erosive burning sensitivity with increasing pressure over the range of conditions studied. As shown in Figure 4, the data also agree well with predictions made with the second generation model. (Recall here that this model is used for the prediction of the V = 0 curve along with the erosive burning curves of Figure 4.) If anything, this model slightly underpredicts the erosive burning sensitivity at the lower crossflow velocities studied while providing excellent agreement with data at a crossflow velocity of 610 m/sec (2000 ft/sec).

Theoretical predictions made with both models and experimental measurements of erosive burning rates for the remaining uncatalyzed, unimodal oxidizer formulations tested (Formulations 5051, 4685, and 5542) are presented in Figures 5 - 10. Formulation 5051, which differs from the baseline formulation through use of 200 micron AP oxidizer in place of 20 micron oxidizer, is predicted by both models to be somewhat more sensitive to crossflow than the baseline formulation. With respect to the first generation model predictions, agreement between predicted and measured augmentation ratio is fairly good except at low pressure, high crossflow velocity conditions, where the measured burning rates considerably exceed the predicted values. However, as may be seen from Figure 6, the second generation model does not exhibit this difficulty, with good agreement between theory and data being obtained over the entire range of test conditions. Breakdown of the first generation model in the low pressure, high crossflow velocity region is not particularly surprising since, in this region, the composite propellant begins to behave more like a homogeneous propellant than a heterogeneous propellant, and this model only considers effects of crossflow on the diffusional mixing processes of oxidizer and fuel streams. In order for the model to be useful in low pressure, high crossflow velocity regions, it appears that an additional mechanism beyond that of flame-bending must be invoked. With the second generation model, this additional mechanism, crossflow-induced turbulence augmentation of transport properties has been included, with the observed beneficial results.

As shown in Figures 7 and 8, Formulation 4685, which differs from the baseline formulation by replacement of 20 micron oxidizer with 5 micron oxidizer, exhibits considerably less sensitivity to erosion than that baseline formulation, as predicted. Agreement between predicted and observed burning rates appears to be good except, again, with the first generation model in the low pressure, high crossflow velocity regime. With Formulation 5542 (analogous to the baseline formulation but with higher oxidizer/fuel ratio and consequently higher temperature and base burning rate, oxidizer size being held constant) the first generation model appears to slightly overpredict the sensitivity of the burning rate to crossflow (Figure 9) while the second generation model does an excellent job of matching data with predictions (Figure 10).

With Formulation 4869, which differs from the baseline formulation through addition of two percent iron oxide catalyst, theoretical predictions have been made only with the first generation model since the second generation model has not yet been expanded to include the effects of burning rate catalysts. As shown in Figure 11, data and theoretical predictions agree fairly well at high crossflow velocities, but not nearly as well at low crossflow velocities where the predictions of erosive burning rate augmentation are somewhat higher than observed in the experiments. An explanation of this discrepancy has not yet been developed.

Theoretical predictions have been made with both the first and second generation models for two additional formulations, both consisting of 18 percent HTPB binder and 82 percent bimodal ammonium perchlorate (Formulations 5555 and 5565). Comparisons of these predictions with data are presented in Figure 12-15. As may be seen from Figures 12 and 13,

Formulation 5555, a high burning rate formulation, is predicted by both models to be rather insensitive to crossflow: the data corroborate this prediction. With Formulation 5565, which has approximately the same base (no-crossflow) burning rate-pressure behavior as the baseline formulation but a considerably higher oxidizer/fuel ratio and flame temperature, good agreement is found between data and the first generation model predictions, the formulation being fairly sensitive to crossflow. However, as shown in Figure 15, the second generation model badly overpredicts this sensitivity. The cause of this problem has not yet been positively identified, but it appears likely that it is associated with inaccurate modeling of the effect of the flow field on either the flame-bending or the turbulence augmentation of transport properties at large distances from the propellant surface. (The combination of the very large 200 micron ammonium perchlorate particle size in this formulation and relatively high burning rate, at least as compared to the other large oxidizer formulations tested to date, leads to very large predicted no-crossflow diffusion flame heights for this formulation.) This possibility is currently being examined and a resolution of the problem sought.

Since the second generation model has not yet been extended to treat metalized formulations and since there is currently an insufficient data base for generation of the optimum values of the three free constants in the model for the polyester binder/AP/Fe_2O_3 propellant family, the data for the remaining three formulations (6626, 7523, and 7605) are compared only to predictions made with the first generation model. (Figures 16-18.)

Predicted and experimental erosive burning characteristics for Formulation 6626, the only metalized formulation tested to date, are presented in Figure 16. Although the data are somehwat sparse, the agreement between experiment and theory appears to be excellent. This is particularly interesting since the first generation flame-bending model used to generate the curves plotted on Figure 16 does not include any specific mechanism involving the aluminum: the excellent agreement with data suggests (though it certainly offers no rigorous proof) that the aluminum, at least at the relatively low level of 5 percent, does not directly affect the erosive burning of composite propellants.

Results for the two polyester formulations (7523 and 7605) are presented in Figure 17 and 18. As may be seen the agreement between theory and experiment is not particularly good for these formulations, especially at high pressure. In both cases the dependence of burning rate on pressure at fixed crossflow velocity seems to be somewhat larger than predicted.

DEFINITION OF FACTORS AFFECTING EROSIVE BURNING SENSITIVITY

In Figure 19, a summary of the effects of various parameters on sensitivity of formulations to crossflow (discussed in more detail below) is presented. Between Formulations 4525, 5051, and 4685, the only independent variable changed is the oxidizer particle size, composition being held constant. The change of oxidizer size, of course, leads to a change in base (no-crossflow) burning rate versus pressure characteristics. Formulation 5051, containing 200 micron diameter AP, is the slowest burning of the three formulations, with Formulation 4685 (5 micron AP) being the fastest and Formulation 4525 (20 micron AP) being intermediate. For instance, at 5 MPa (50 atmospheres) the base burning rate of 5051 is 0.47

cm/sec, that of 4525 is 0.68 cm/sec and that of 4685 is 1.15 cm/sec. Examination of Figures 2, 5, and 7 indicates that the sensitivity of burning rate to crossflow increases with increasing particle size (decreasing base burning rate). For example, at a crossflow velocity of 200 m/sec (650 ft/sec) and a pressure of 5 MPa (50 atmospheres), the augmentation ratio (ε) for 4685 is about 1.10, that for 4525 is 1.65, and that for 5051 is 2.0.

Comparison of data for 4525 and 4869, two formulations of essentially the same oxidizer/fuel ratio, flame temperature, and oxidizer particle size, with the base burning rate being varied through use of catalyst in 4869, again shows an increase in sensitivity of burning rate to crossflow with a decrease in burning rate. At 5 MPa (50 atmospheres) the base burning rates for 4869 and 4525 are 1.40 cm/sec and 0.68 cm/sec, respectively. At this pressure, with a crossflow velocity of 200 m/sec (650 ft/sec), their r/r_o values are 1.10 and 1.65, respectively, while at 600 m/sec (1950 ft/sec), the r/r_o values are 1.75 and 2.3. Thus base burning rate is seen to affect the erosion sensitivity of composite propellants even at constant oxdizer particle size, erosive effects increasing with decreasing base burning rate.

Formulations 4685 and 4869 have approximately the same base burning rate at 8 MPa (80 atmospheres) with catalyst and oxidizer particle size effects on base burning rate roughly cancelling. Thus comparison of erosion sensitivity of these formulations at this pressure is of interest in that oxidizer particle size is varied (5 micron diameter for 4685, 20 micron diameter for 4869) while base burning rate is held constant. Comparison of data from Figures 7 and 11 indicates that these formulations have roughly the same sensitivity to the lower crossflow velocities tested at 8 MPa (80 atmospheres), with the catalyzed propellant being slightly more sensitive at the higher crossflow velocities tested. Thus it appears that it is the base burning rate rather than the oxidizer particle size *per se* which dominates the sensitivity of composite propellants to erosive burning, though oxidizer size does have some further residual effects, erosion sensitivity decreasing with decreasing particle size at constant base burning rate.

Comparison of test results for Formulations 4525, 5542 and 5565 permits study of the effect of oxidizer/fuel ratio (and thus flame temperature) on erosion sensitivity, both at constant oxidizer particle size (5542 and 4525) and at constant base burning rate (5565 and 4525). Formulation 5542 differed from 4525 in oxidizer/fuel ratio (77/23 versus 73/27) and consequently flame temperature (2065°K vs 1667°K). Since the oxidizer particle size was the same for both propellants, the higher oxidizer/fuel ratio for 5542 led to higher base burning rate (1.14 cm/sec vs. 0.68 cm/sec at 5 MPa). Study of Figures 2 and 9 reveals that the erosion sensitivity of 5542 is considerably less than that of 4525 over the entire range of crossflow velociities studied (e.g., r/r_o = 1.10 for 5542 and 1.65 for 4525 at 200 cm/sec, 5 MPa; and r/r_o = 1.7 for 5542 and 2.9 for 4525 at 800 m/sec, 5 MPa). Thus we see that changing oxidizer/fuel ratio from very fuel- rich to less fuel-rich, with accompanying increase in flame temperature and burning rate, leads to decreased sensitivity to erosive burning. Comparison of results for 5565 and 4525, which differ in oxidizer/fuel ratio but not in base burning rate (oxidizer particle size having been adjusted to compensate for the burning rate change with changing

oxidizer/fuel ratio) permits separation of the effects of varying oxidizer/fuel ratio (and thus flame temperature) from the effects of base burning rate. As may be seen by study of Figures 2 and 14, the sensitivity of Formulations 5565 and 4525 to crossflow are nearly the same. For instance, at 200 m/sec (650 ft/sec) crossflow velocity and 5 MPa (50 atmospheres), the augmentation ratios for 5565 and 4525 are 1.50 and 1.65, respectivley, while at 800 m/sec (2600ft/sec) and 3 MPa (30 atmospheres), they are 2.65 and 2.50. Accordingly, we may tentatively conclude that oxidizer/fuel ratio (and consequently flame temperature) does not directly affect the erosion sensitivity of the compositions studied to date, but only affects it through its effect on base burning rate.

Formulations 5555 and 5565 had the same composition, differing only in oxidizer particle size, which was adjusted in 5555 to give a very high burning rate. Again, the effect on erosion sensitivity of increased base burning rate can be seen in comparison of Figures 12 and 14. At 5 MPa (50 atmospheres), the base burning rates of 5555 and 5565 are 2.94 and 0.70 cm/sec, respectively. At 200 m/sec (650 ft/sec) crossflow velocity, the respective values of r/r_0 are 1.0 and 1.5, while at 700 m/sec (2300 ft/sec), they are 1.2 and 2.4. Thus, once again, erosion sensitivity is seen to decrease with increasing base burning rate.

As mentioned earlier, Formulation 6626, the only metalized formulation tested to date, was tailored to have essentially the same base burning rate versus pressure characteristics as Formulations 4525 and 5565 and, moreover, to have approximately the same flame tmeperature as 5565. It has already been pointed out that comparison of Figures 2 and 14 reveals that Formulations 4525 and 5565 also have nearly identical erosive burning behavior. Comparison of Figure 16 with Figures 2 and 14 reveals further that Formulation 6626 has essentially identical erosive burning behavior as the other two formulations. For example, at a crossflow velocity of 700 m/sec (2300 ft/sec) and a pressure of 2.8 MPa (28 atmospheres) the augmentation ratios for 4525, 5565, and 6626 are 2.05, 2.20, and 2.05; while at 245 m/sec (800 ft/sec) and 4.0 MPa (40 atmospheres), they are 1.80, 1.63, and 1.71. Thus, we are again drawn to a conclusion that the dominant factor affecting the sensitivity of burning rate of a composite propellant to crossflow is the base burning rate, largely independent of the various factors going into determining that base burning rate.

With respect to the effect of binder type on erosion sensitivity, comparison of Figures 11 and 17 is useful. With Formulations 4869 and 7523, the base burning rate and oxidizer size were held constant while the binder was changed from HTPB to polyester (the latter yielding a higher flame temperature). Study of the figures indicates that at low pressure the erosion sensitivities of these two formulations were essentially equal but that at higher pressures the polyester formulation was more sensitive to crossflow. A similar conclusion is drawn from comparison of data for Formulations 5542 and 7605, presented in Figures 9 and 18. Between these latter two formulations, base burning rate was again held essentially constant though in this case the oxidizer particle size(s) did vary.

SUMMARY

Eight AP/HTPB propellants and two polyester/AP formulations with systematically varied compositions and ingredient particle sizes have been characterized with respect to erosive burning over a wide range of pressures and crossflow velocities. The erosive burning data have been compared with predictions made using a simplified first-generation model in which it is postulated that erosive burning is caused solely by bending of columnar diffusion flames by a crossflow. In general, the model was found to reasonably well predict the observed results except at low pressure, high crossflow velocity conditions where the composite propellant heterogeneity is relatively unimportant. A considerably more sophisticated model, capable of predicting burning rate as a function of pressure and crossflow velocity (including the limiting case of zero crossflow velocity) given only propellant compositional and ingredient particle size data has been tested against data obtained for six of the AP/HTPB formulations. In all cases, the model predicts the no-crossflow results quite well, and in five out of six cases it additionally does an excellent job in predicting erosive burning characteristics, even in the low pressure, high crossflow velocity regime (due to inclusion of a second erosive burning mechanism, crossflow-induced turbulence augmentation of transport properties). Data obtained to date support the following general conclusions regarding the effects of various parameters on the sensitivity of composite propellant burning rate to crossflow:

(1) The severity of erosive burning (augmentation ratio) is most strongly dependent on base (no-crossflow) burning rate, augmentation ratio increasing with decreasing base burning rate.

(2) There is a small residual effect of oxidizer particle size at fixed base burning rate, erosion sensitivity decreasing with decreased particle size.

(3) Oxidizer/fuel ratio (and thus flame temperature) appears to affect the augmentation ratio for HTPB systems only through its effect on the base burning rate.

(4) At fixed base burning rate, aluminum has no effect on erosive burning, at least at the low (5 percent) aluminum loading tested thus far.

(5) The interaction of effects of crossflow velocity and pressure on burning rate appears to be different for polyester and HTPB binder systems, the polyester formulations being more sensitive to crossflow at high pressure.

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TABLE I. PROPELLANT MATRIX BEING TESTED.

TEST SET	FORMULATION	COMPOSITION	RATIONALE
1	4625	73/27 AP/HTPB, 20μAP	BASELINE FORMULATION, T = 1667 °K
2	5051	73/27 AP/HTPB, 200μAP	COMPARE WITH 1 FOR AP SIZE EFFECT
3	4685	73/27 AP/HTPB, 5μAP	COMPARE WITH 1 AND 2 FOR AP SIZE EFFECT
4	4880	72/26/2 AP/HTPB/Fe_2O_3, 20μAP	COMPARE WITH 1 FOR BR EFFECT AT CONSTANT AP SIZE
5	5542	77/23 AP/HTPB, 20μAP	COMPARE WITH 1 FOR MIX RATIO (TEMPERATURE) EFFECT AT CONSTANT AP SIZE. T = 2065°K
6	7623	70/28/2 AP/POLYESTER/Fe_2O_3(20μAP)	BASELINE POLYESTER FORMULATION, T =2250°K, AP SIZE CHOSEN TO MATCH BR OF NO. 4. COMPARE WITH NO. 4 FOR BINDER EFFECT.
7	5565	82/18 AP/HTPB, BIMODAL AP (68.33 % 200μ, 13.65% 90μ)	MEDIUM TEMPERATURE HTPB FORMULATION. AP SIZES CHOSEN TO MATCH BR OF NO. 1, COMPARE WITH NO. 1 FOR TEMPERATURE EFFECT T = 2575°K.
8	5585	82/18 AP/HTPB, BIMODAL AP (41 % 1μ, 41 % 7μ)	COMPARE WITH NO. 7 FOR BR EFFECT. T = 2575°K.
9	7605	78/20/2 AP/POLYESTER/Fe_2O_3, BIMODAL AP (23.4 % 20μ, 54.6 % 200μ)	MEDIUM TEMP. (2800°K) SMOKELESS POLYESTER FROMULATION. COMPARE WITH NO. 6. ALSO COMPARE WITH NO. 5 FOR BINDER EFFECT AT NEARLY CONSTANT BR.
10	7759	88 AP/12 HTPB, MULTIMODAL AP	ARCADENE 368 (OPERATIONAL SMOKELESS PROPELLANT)
11	6626	74 AP/21 HTPB/5 Al, MULTIMODAL AP TO MATCH BR OF NO. 7.	SAME TEMPERATURE AS NO. 7. COMPARE WITH NO. 7 FOR ALUMINUM EFFECT.
A1	7758	82/18 AP/HTPB, BIMODAL AP (41 % 7μ, 41 % 90μ)	FURTHER STUDY OF AP SIZE AND BASE BURNING RATE EFFECTS
A2	7748	82/18 AP/HTPB, BIMODAL AP (41 % 20μ, 41 % 20μ)	
A3	7750	82/18 AP/HTPB, TRIMODAL AP (27.3 % 1μ, 27.3 % 20μ, 27.4 % 200μ)	

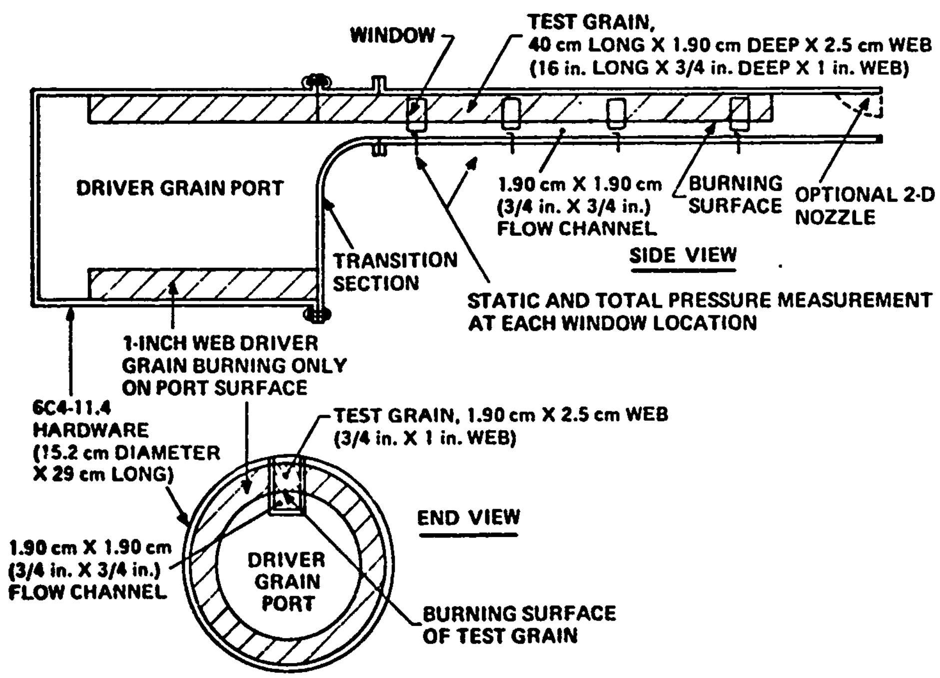

FIGURE 1. SCHEMATIC OF ATLANTIC RESEARCH EROSIVE BURNING TEST APPARATUS.

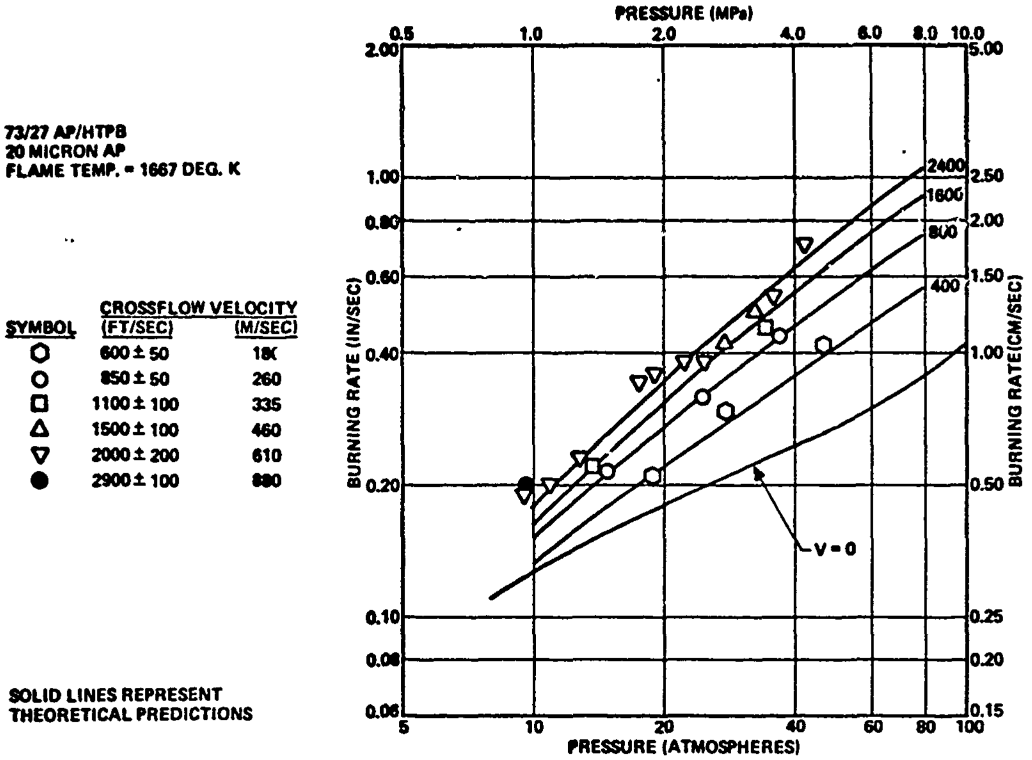

FIGURE 2. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 4525.

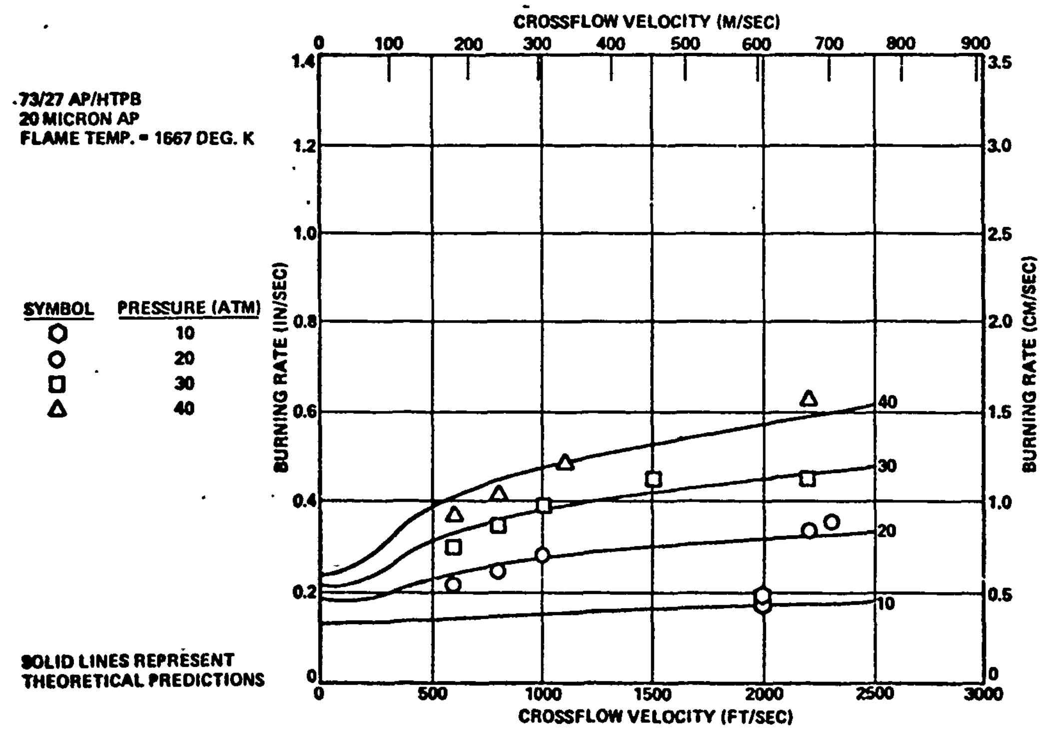

FIGURE 3. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 4525.

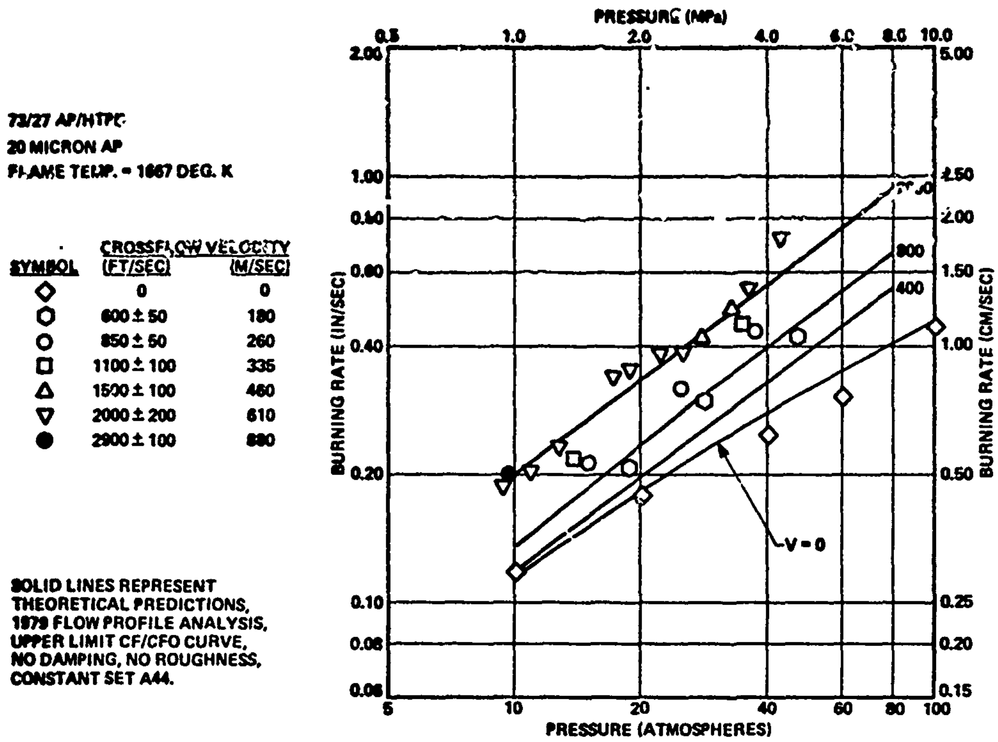

FIGURE 4. EROSIVE BURNING DATA COMPARED WITH SECOND GENERATION MODEL PREDICTIONS FOR FORMULATION 4525.

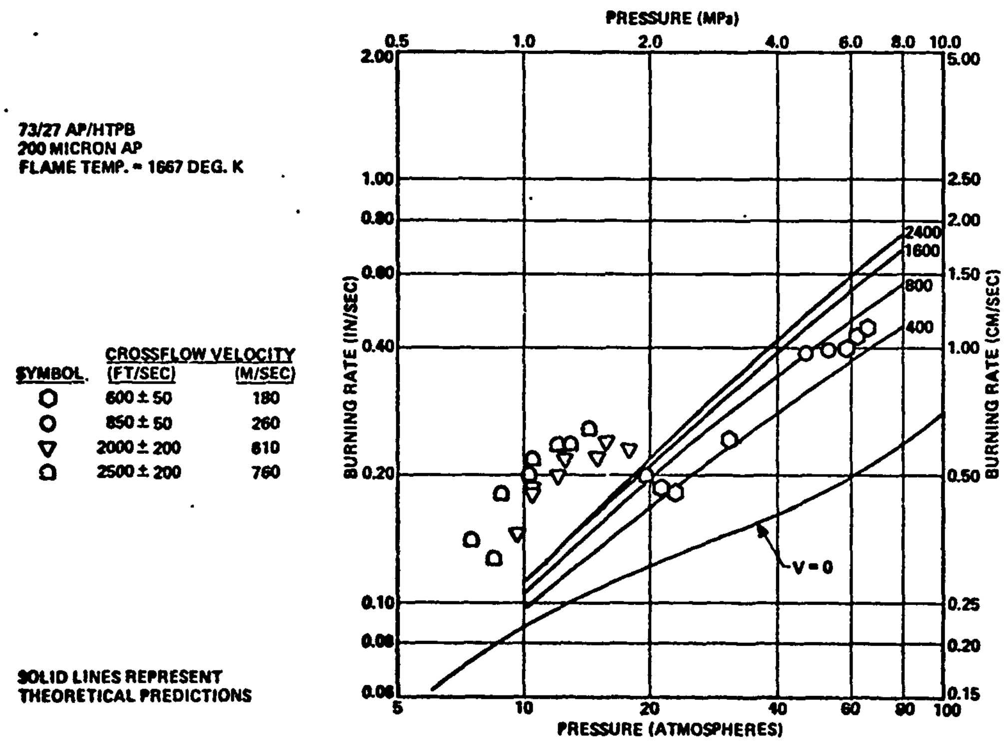

FIGURE 5. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 5051.

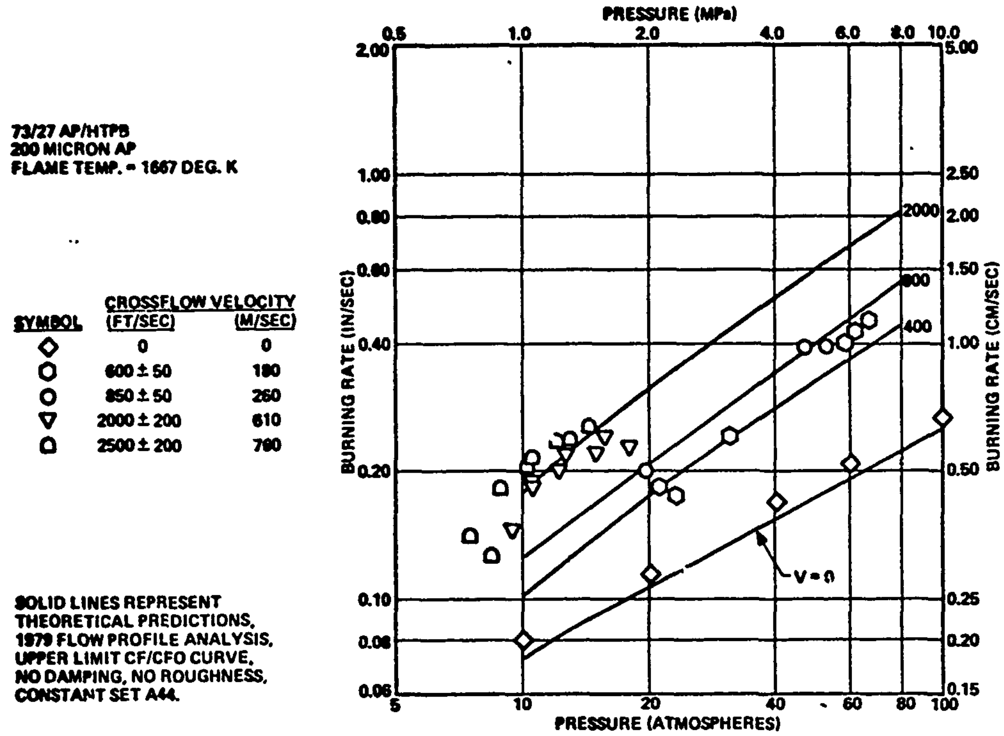

FIGURE 6. EROSIVE BURNING DATA COMPARED WITH SECOND GENERATION MODEL PREDICTIONS FOR FORMULATION 5051.

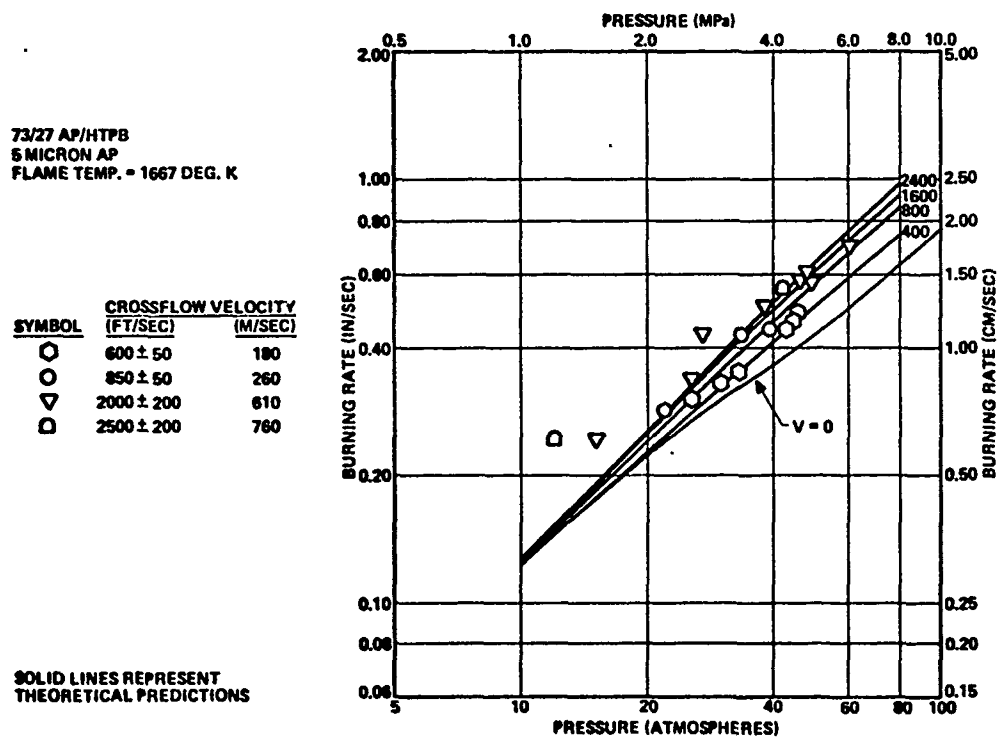

FIGURE 7. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 4685.

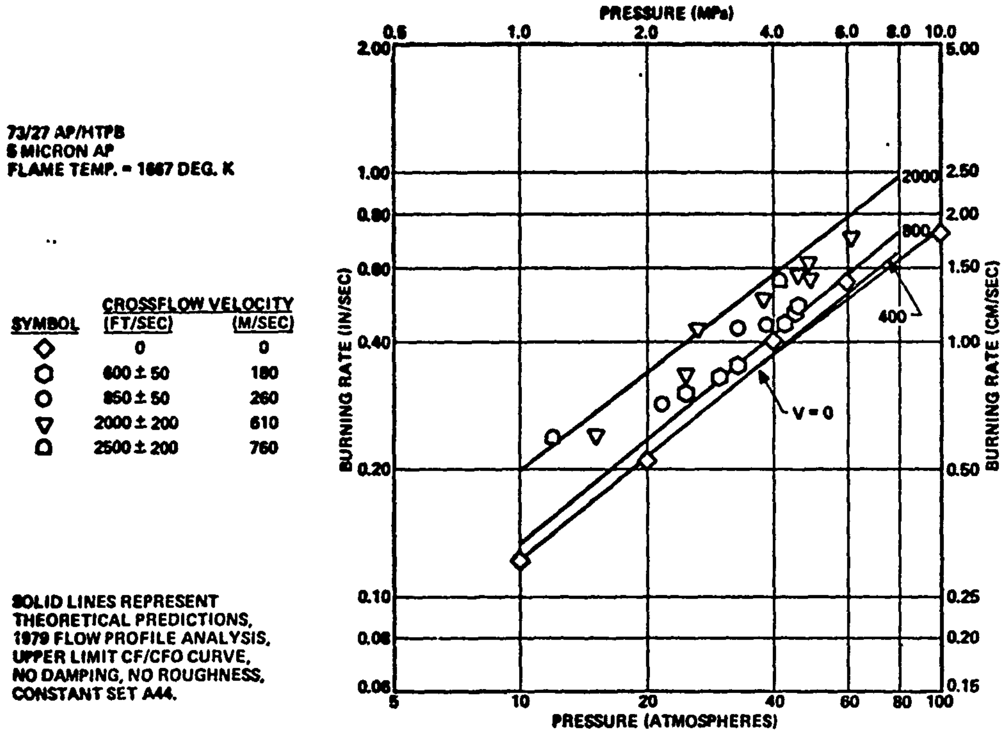

FIGURE 8. EROSIVE BURNING DATA COMPARED WITH SECOND GENERATION MODEL PREDICTIONS FOR FORMULATION 4685.

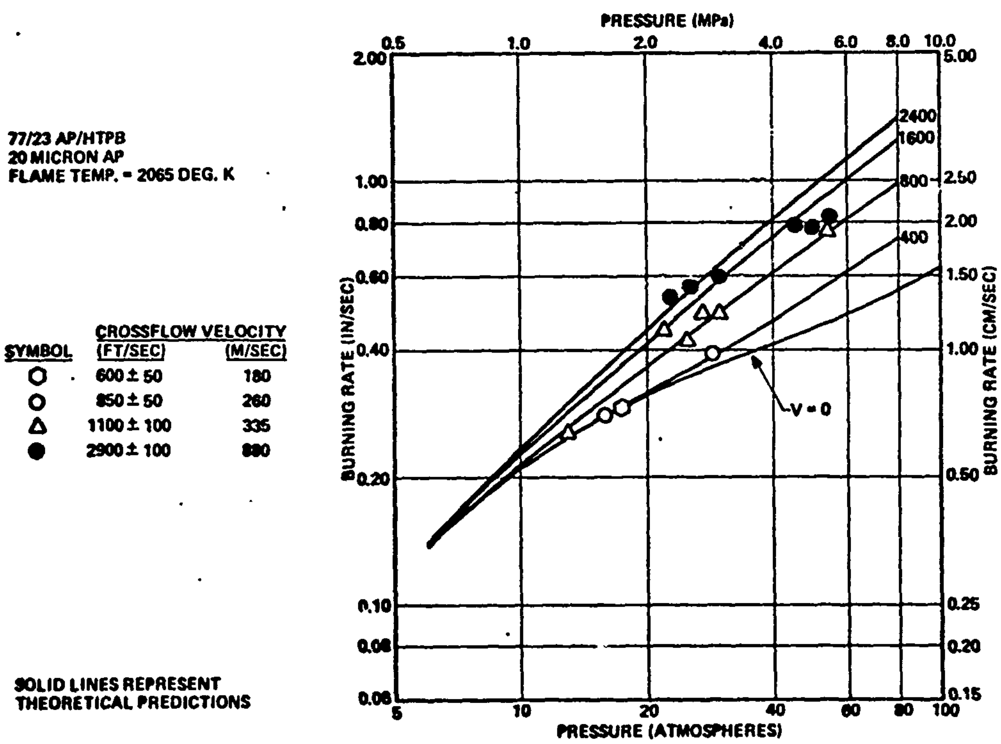

FIGURE 9. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 5542.

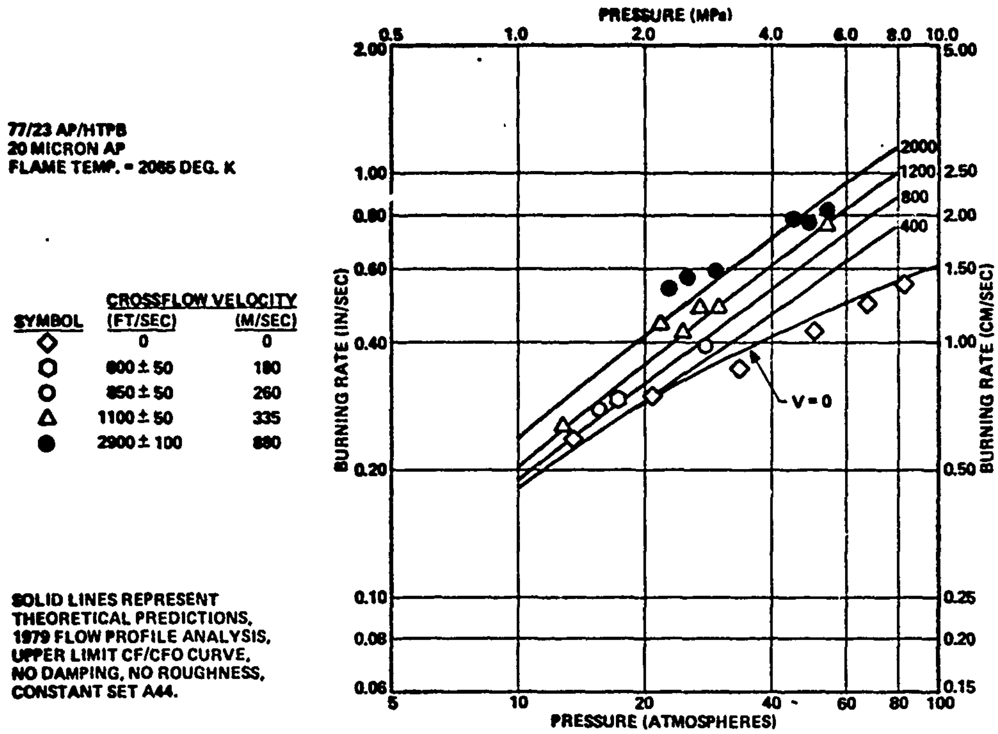

FIGURE 10. EROSIVE BURNING DATA COMPARED WITH SECOND GENERATION MODEL PREDICTIONS FOR FORMULATION 5542.

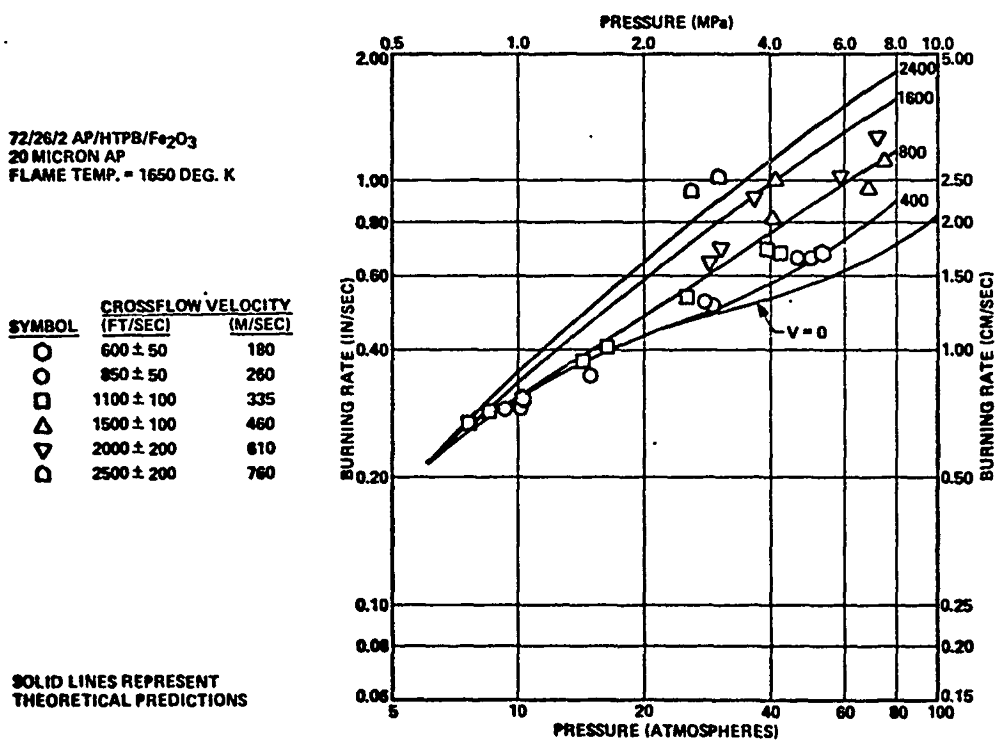

FIGURE 11. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 4869.

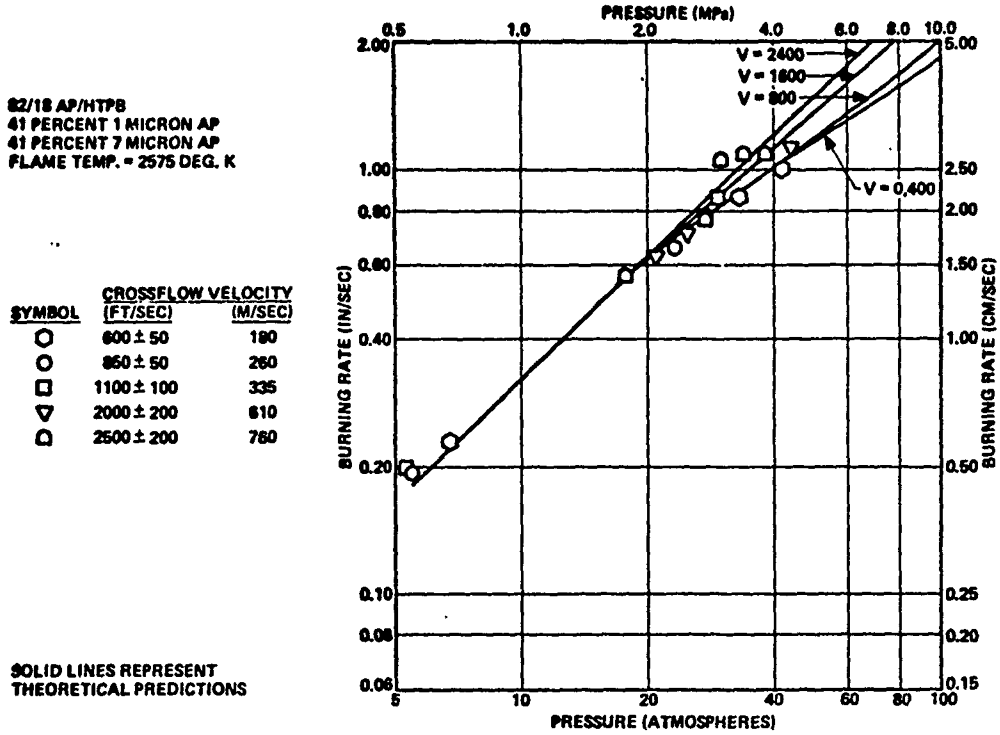

FIGURE 12. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 5555.

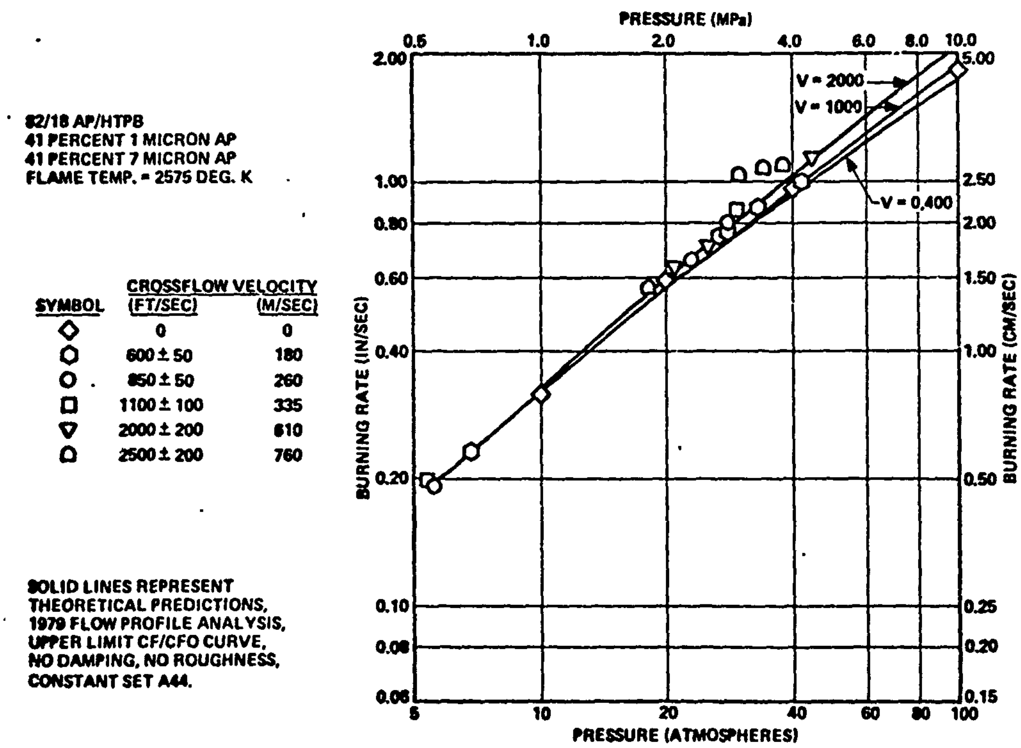

FIGURE 13. EROSIVE BURNING DATA COMPARED WITH SECOND GENERATION MODEL PREDICTIONS FOR FORMULATION 5555.

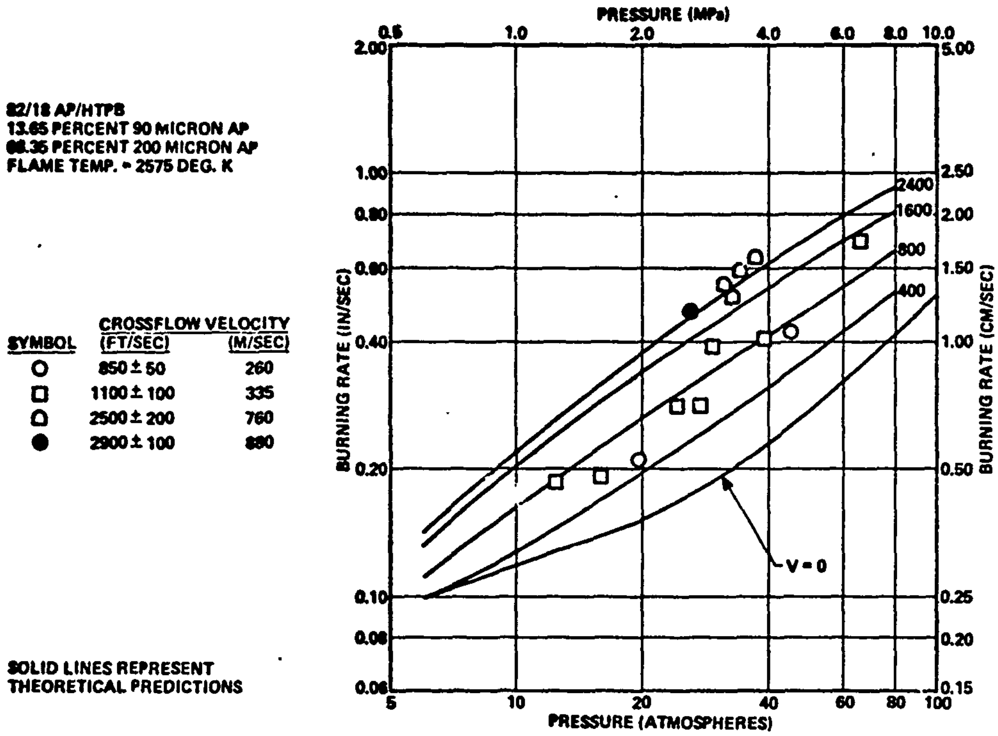

FIGURE 14. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 5565.

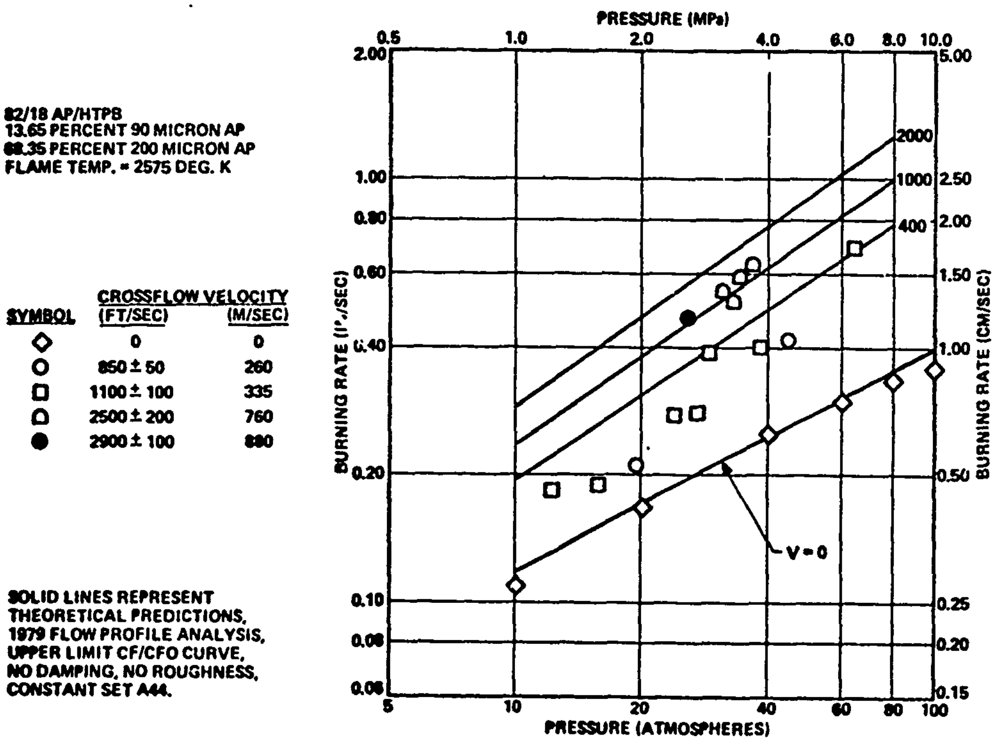

FIGURE 15. EROSIVE BURNING DATA COMPARED WITH SECOND GENERATION MODEL PREDICTIONS FOR FORMULATION 5565.

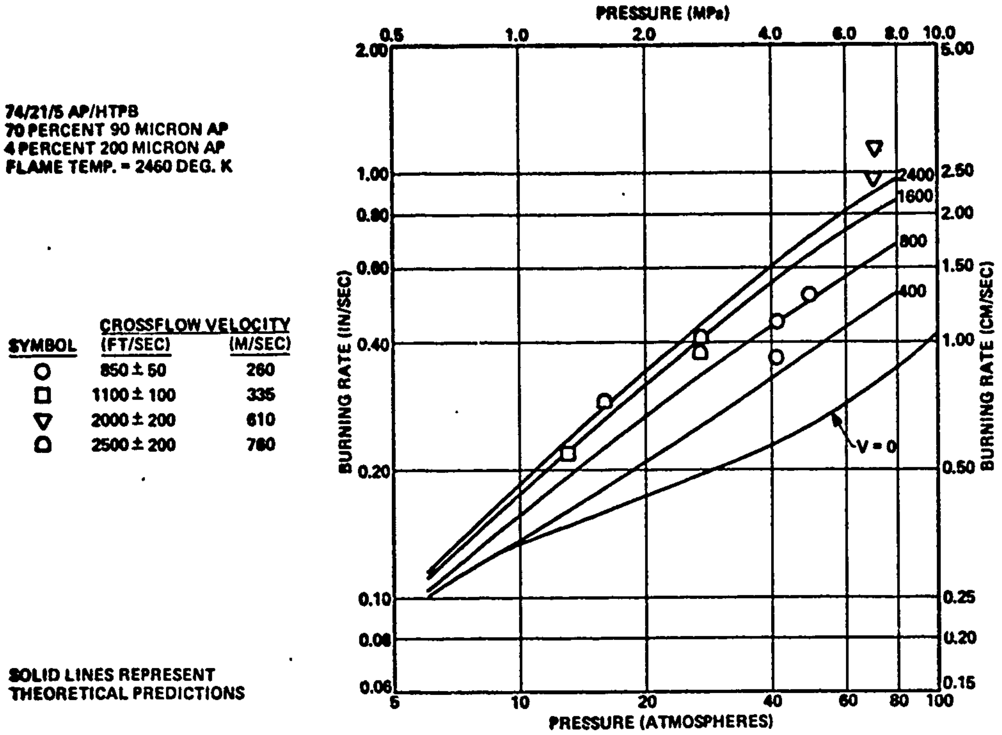

FIGURE 16. EROSIVE BURNING DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 6626.

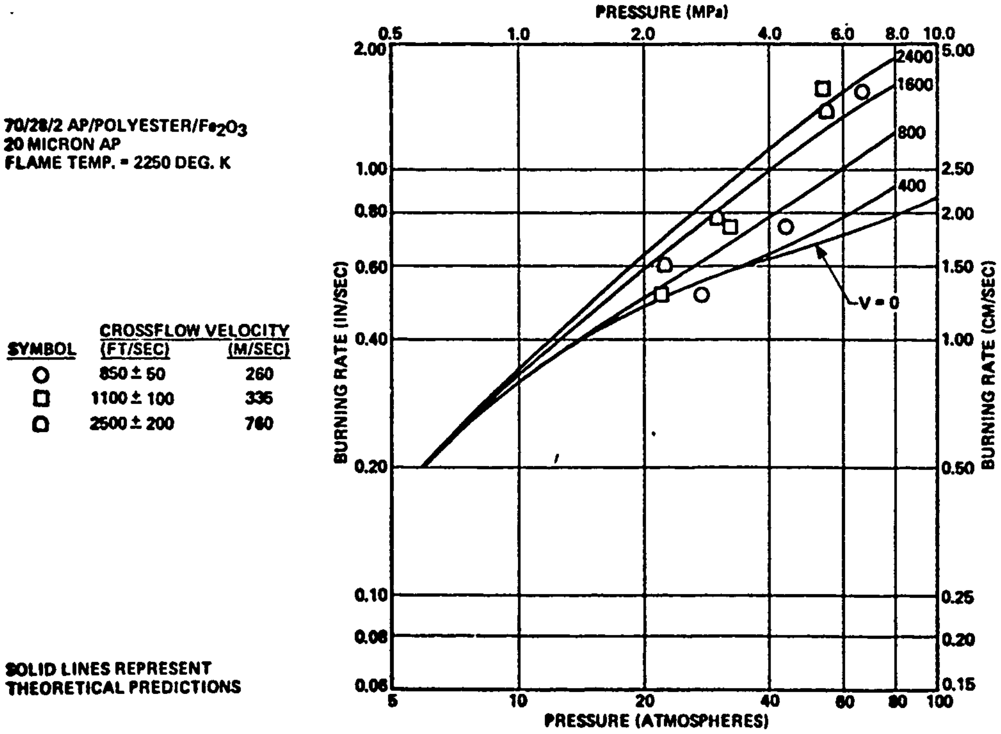

FIGURE 17. EROSIVE BURNING RATE DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 7523.

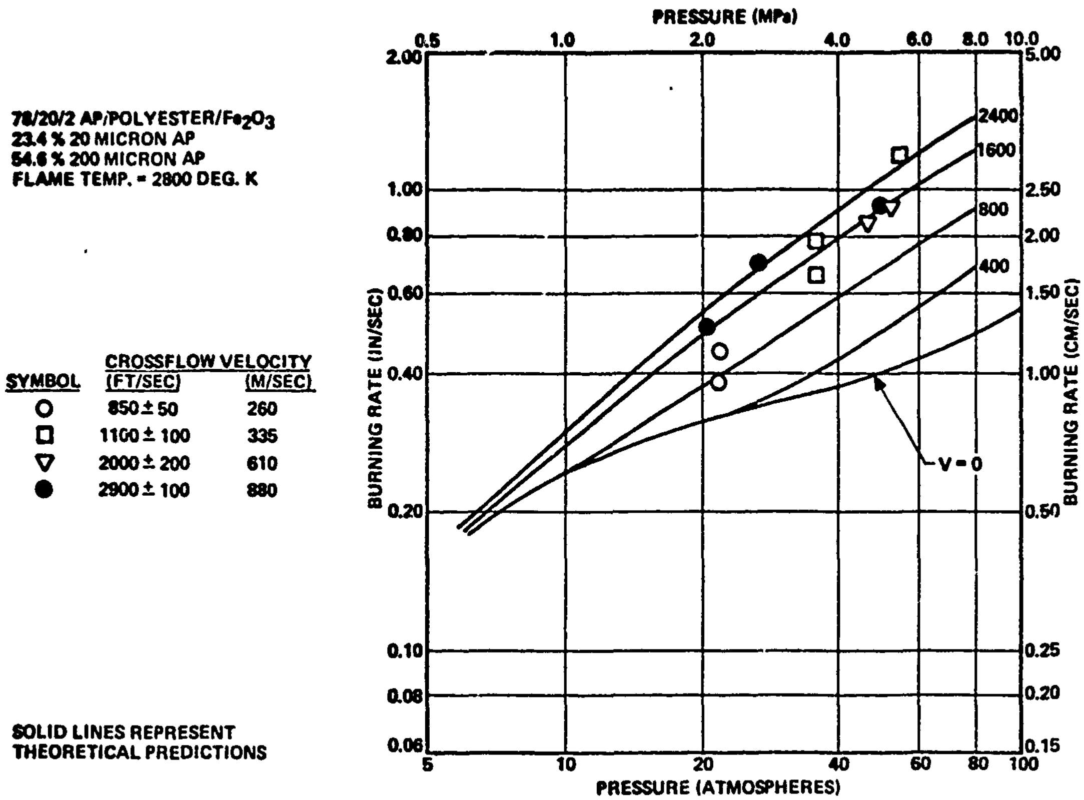

FIGURE 18. EROSIVE BURNING RATE DATA COMPARED WITH FIRST GENERATION MODEL PREDICTIONS FOR FORMULATION 7605.

COMPARISON	PARAMETERS STUDIED	EFFECT ON EROSIVE BURNING
4525, 5051, 4685	VARIED d_p, r_o AT FIXED BINDER TYPE, FIXED FLAME TEMPERATURE	$d_p \downarrow \longleftrightarrow r_o \uparrow \rightarrow \epsilon \downarrow$
4525, 4869	VARIED r_o AT FIXED AP SIZE, BINDER TYPE, AND FLAME TEMPERATURE	$r_o \uparrow \rightarrow \epsilon \downarrow$
4685, 4869	VARIED d_p AT FIXED r_o, BINDER TYPE, AND FLAME TEMPERATURE	$d_p \downarrow \rightarrow \epsilon \downarrow$ SLIGHTLY
4525, 5542	VARIED O/F RATIO (AND THUS FLAME TEMPERATURE) AND r_o AT FIXED BINDER TYPE AND FIXED AP SIZE	$T_f \uparrow \longleftrightarrow r_o \uparrow \rightarrow \epsilon \downarrow$
5665, 4525	VARIED O/F RATIO (AND THUS FLAME TEMPERATURE) AT FIXED BINDER TYPE AND FIXED r_o	$T_f \uparrow \rightarrow \epsilon$ UNCHANGED
5665, 5555	VARIED d_p, r_o AT FIXED BINDER TYPE, FIXED FLAME TEMPERATURE	$d_p \downarrow \longleftrightarrow r_o \uparrow \rightarrow \epsilon \downarrow$
5665, 6626	ALUMINUM VERSUS NON-ALUMINUM AT FIXED r_o, BINDER TYPE, AND FLAME TEMPERATURE	Al $\longrightarrow \epsilon$ UNCHANGED
4869, 7523	DIFFERENT BINDER TYPE; r_o, d_p HELD CONSTANT; DIFFERING FLAME TEMPERATURE (POLYESTER HOTTER)	AT LOW P, ϵ UNCHANGED AT HIGH P, ϵ HIGHER FOR POLYESTER
5642, 7605	DIFFERENT BINDER TYPE; r_o HELD CONSTANT; DIFFERING FLAME TEMPERATURE (POLYESTER HOTTER) AND d_p	AT LOW P, ϵ UNCHANGED AT HIGH P, ϵ HIGHER FOR POLYESTER

FIGURE 19. EFFECTS OF VARIOUS PARAMETERS ON SENSITIVITY OF FORMULATIONS TO CROSSFLOW.